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## Finite element analysis of pathogenesis of osteoarthritis in the first carpometacarpal joint.

Qilin Shi\*

Hiroyuki Hashizume<sup>†</sup>

Hajime Inoue<sup>‡</sup>

Toshiyuki Miyake\*\*

Noriyuki Nagayama<sup>††</sup>

\*Okayama University,

<sup>†</sup>Okayama University,

<sup>‡</sup>Okayama University,

\*\*Okayama University,

<sup>††</sup>Industrial Technology Center of Okayama Prefecture,

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Qilin Shi, Hiroyuki Hashizume, Hajime Inoue, Toshiyuki Miyake, and Noriyuki Nagayama

## Abstract

Stress distribution in the first carpometacarpal joint was analyzed in 49 cadaveric hands using the finite element method to clarify the pathogenesis of osteoarthritis in the joint. The results of the finite element method analysis were compared with those of the contact pressure distribution in the first carpometacarpal joint of cadaveric specimens using pressure-sensitive film, and with the simple roentgenographical and microradiographical manifestations of spur formation, and with histological findings of osteoarthritis to verify the accuracy of the models of computer simulation models. The comparison of these results showed that osteoarthritic changes of the first carpometacarpal joint were found in areas where stress was concentrated during movement of the joint. The saddle shape of this joint is essentially well-designed for the dispersion of normal stress, however minimal displacement due to instability could easily induce osteoarthritis. Furthermore the shallow trapezial configuration may contribute to the high incidence of osteoarthritis changes. The finite element method helped clarify the relationship between stress patterns and osteoarthritis response.

**KEYWORDS:** carpometacarpal joint, onset mechanism of osteoarthritis, stress distribution analysis, twodimensinoal finite element method, pressure-sensitive film

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# Finite Element Analysis of Pathogenesis of Osteoarthritis in the First Carpometacarpal Joint

Qilin SHI, Hiroyuki HASHIZUME\*, Hajime INOUE, Toshiyuki MIYAKE and Noriyuki NAGAYAMA<sup>a</sup>

Department of Orthopaedic Surgery, Okayama University Medical School, Okayama 700, Japan and <sup>a</sup>Industrial Technology Center of Okayama Prefecture, Okayama, 701-01, Japan

Stress distribution in the first carpometacarpal joint was analyzed in 49 cadaveric hands using the finite element method to clarify the pathogenesis of osteoarthritis in the joint. The results of the finite element method analysis were compared with those of the contact pressure distribution in the first carpometacarpal joint of cadaveric specimens using pressure-sensitive film, and with the simple roentgenographical and microradiographical manifestations of spur formation, and with histological findings of osteoarthritis to verify the accuracy of the models of computer simulation models. The comparison of these results showed that osteoarthritic changes of the first carpometacarpal joint were found in areas where stress was concentrated during movement of the joint. The saddle shape of this joint is essentially well-designed for the dispersion of normal stress, however minimal displacement due to instability could easily induce osteoarthritis. Furthermore the shallow trapezoidal configuration may contribute to the high incidence of osteoarthritis changes. The finite element method helped clarify the relationship between stress patterns and osteoarthritis response.

**Key words:** carpometacarpal joint, onset mechanism of osteoarthritis, stress distribution analysis, two-dimensional finite element method, pressure-sensitive film

**D**isease or injury of the first carpometacarpal joint (CMJ) often leads to a debilitating loss of hand function. Idiopathic osteoarthritis (OA) may be the most common cause of pathological changes in this joint.

Traumatic damage, deformity of the articular surface, and ligamentous instability due to trauma, inflammation, and idiopathic instability are also believed to be contributory factors. Acute instability can be caused by severe trauma, however, slowly progressive and chronic idiopathic ligament instability, sometimes seen in young women with generalized ligament laxity, can be caused by recurrent stress or overuse. A very shallow trapezium saddle contour may also explain onset in some cases (1). For a large number of patients, however, the pathogenesis of OA in the CMJ is still obscure.

Based on the assumption that stress concentration on the joint surface could be a principal factor in the onset mechanism of OA (2, 3) if any other pathological condition preexists, a three-part biomechanical approach was used to investigate the pathogenesis of degeneration of the CMJ in the present study. The first method was the two-dimensional finite element method (FEM). In the second method, contact pressure distribution in the CMJ of cadaveric specimens was measured using pressure-sensitive film. The third method was simple roentgenographical, microradiographical and histological observation of the cadaveric specimens including details of cartilaginous degeneration and bony spur. We compared the results of these three analyses, and discuss them in terms of the pathogenesis of OA of the CMJ.

## Materials and Methods

Four amputated and 49 cadaveric specimens were used for this three-part approach. The amputated hands taken from young patients with malignant tumor of the upper extremity were used to create the FEM model after simple roentgenographical examination because there were

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\* To whom correspondence should be addressed.

no OA changes. They were also used as the control groups against the OA groups. Cadavers were divided into two groups after simple roentgenographical examinations. Specimens with minimal signs of OA (North's classification, Stage I) (1) were grouped for the loading test. The other group, with simple roentgenographical OA changes, was used for microradiographical and histological observations.

**FEM analysis.** The structural data for making FEM models were obtained from serially sectioned specimens of the first CMJ of four amputated right hands (two men and two women, aged 18 to 25 years). The first metacarpal bone and trapezium were extracted with intact joint and soft tissues. A single, central, 1-mm longitudinal section was removed for the study from both bones of each specimen. Specimens from one man and one woman were used for the anteroposterior view model, and the other man and woman yielded sections for the lateral view model. We used a BS-3000 micro cutting-machine for calcified materials (Exact Co., Germany). The outline and thickness for each two-dimensional FEM model was determined by tracings of the microradiographic films. The trabecular patterns along the joint were also observed to determine the direction of stress in each two-dimensional slice.

Four different material properties were applied corre-

sponding to cortical bone, subchondral bone, cancellous bone and cartilage. Young's moduli were 15,000 MPa for cortical bone, 1,000 MPa for subchondral bone, 100 MPa for cancellous bone, and cartilage was 5 MPa. Poisson's ratios were 0.3 for cortical bone, 0.2 for subchondral bone, 0.2 for cancellous bone, and 0.49 for cartilage (4). Loading conditions were determined by the relative position of the members and estimation of the amount of pressure that was applied to the trapezium (3) and directed parallel to the trabecular pattern of the first metacarpal base. A general FEM program (MARC, MARC Analysis Research Corp., USA) was used for computer simulation analysis. In the anteroposterior view, 217 elements and 246 nodal points were used for the first metacarpal bone and 81 elements and 95 nodal points for the trapezium. In the lateral view, 187 elements and 221 nodal points were used for the first metacarpal bone and 78 elements and 93 nodal points for the trapezium. Computer simulation was done for each model (normal anteroposterior view and lateral view models, and shallow trapezium surface model) and for each joint position (neutral, 10-degree radial and ulnar position; 2 mm radial and ulnar shift position) on a workstation (Sun Microsystems, Inc. USA).

**Pressure-loading experiment.** Four pairs of the first metacarpal and trapezium bones from intact

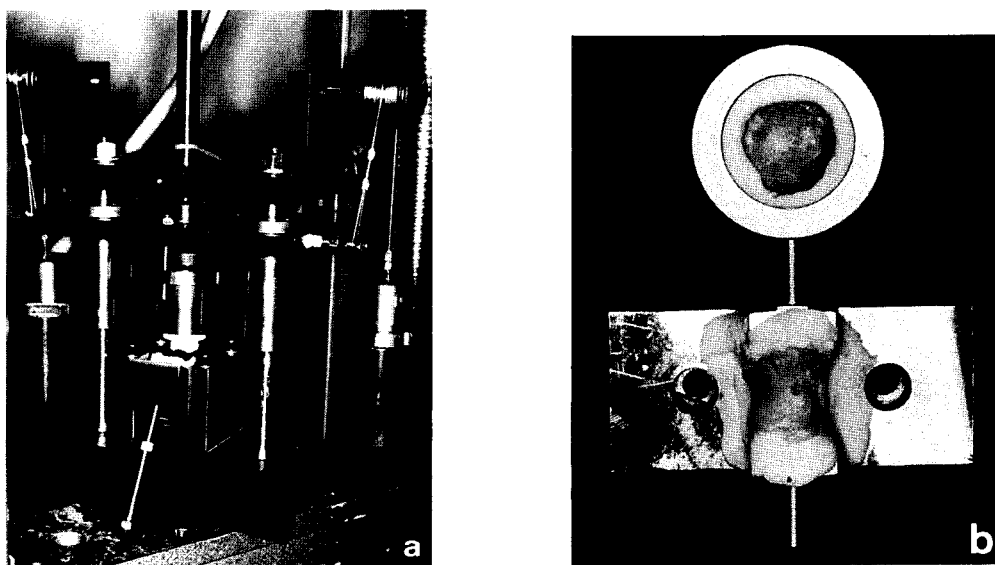


Fig. 1 Contact pressure measurement of a cadaveric specimen using pressure-sensitive film. a. bone fixator and loading machine. b. carpometacarpal joint in the fixator.

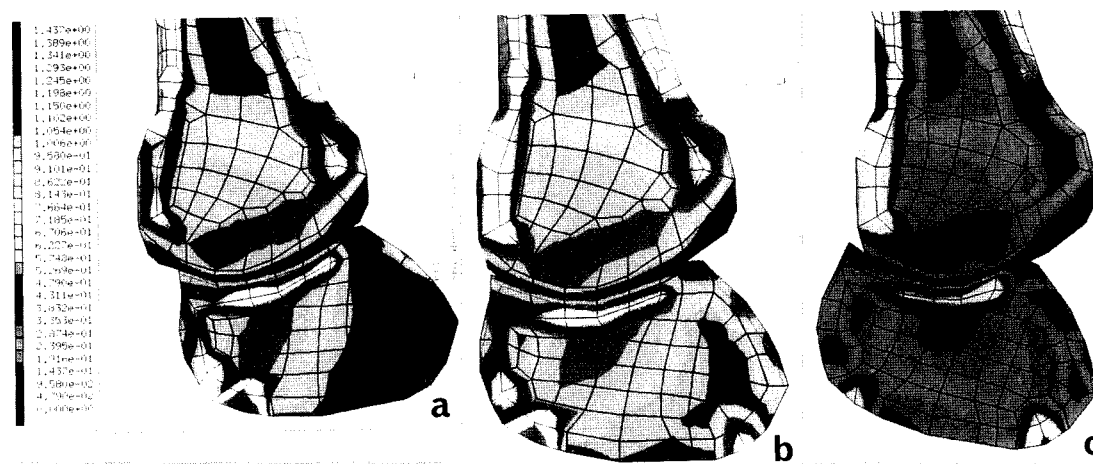
cadaveric CMJ specimens without surrounding soft tissue were used for the pressure-loading experiment. The bony ends of these joints were fixed in a custom bone-fixator with dental resin (Fig. 1). The loading-test machine (Autograpc S2000, Shimadzu Corp., Tokyo, Japan) needed the position of the two instantaneous centers for each individual to properly align the joint to avoid distortion and possible dislocation of the specimen. The specimen also had to be repositioned for testing along a given arc. The CMJ has multiple angles of movements, but we tested only two directions; flexion-extension, and radial-ulnar deviation arcs of movement around each axis of rotation (5). The instant centers of the arcs for the first metacarpal and trapezium bones were determined according to the method of Hurukawa (6). Measurements were made at approximately 10-degree increments. All experimental models were designed according to the simulation of the FEM models.

We measured patterns of pressure areas on Fuji prescale pressure-sensitive film at specific angles along the flexion-extension arc and the radial-ulnar deviation arc. The pattern of pressure loading was measured by inserting the pressure-sensitive film between the two bones in the dry joint. The load deformation curves were plotted in the autograph. We analyzed the loading force in each position, and the pattern of pressure areas using Macintosh NIH imaging software (J-System) to get more finely divided color gradations. The comparative amounts of pressure were also demonstrated on the graphs using the same software.

**Roentgenographical and histological observations.** Thirty-two Japanese cadavers (49 hands) were used: 10 females (14 hands) and 22 males (35 hands). Ages ranged from 50 to 93 years (average age, 69 years). The CMJ with intact soft tissues around the joint was extracted from the cadaveric hands. Conventional roentgenographical examinations of each specimen in the anteroposterior and lateral views were done. These roentgenographs were classified into four stages of OA of the CMJ according to North's system of staging (2). Then both bones of each joint specimen were serially sectioned parallel to the sagittal plane (along the longitudinal axis of the thumb perpendicular to the nail or pulp surface) in 2-mm wide slices with the micro cutting-machine. Serial sections were made from the radial side to the ulnar side and microradiographical examination of sections of each joint ( $n = 20$ ) was done. The area and volume of spur formation were measured. The articular surfaces of each slice (10 CMJs) were removed and stained with hematoxylin-eosin (HE), safranin-O, Masson-trichrome, Mallory-Azan and truidine-blue, and observed by light microscopy. The specimens were graded histologically in three parts (volar, central and dorsal) of each slice according to histological changes.

## Results

**FEM analysis.** Stress in the analysis of the anteroposterior view model tended to be evenly distributed at each angle in the CMJ, with a slight concentration



**Fig. 2** Anteroposterior view of well distributed FEM image of normal position showing stress in the trapezium and proximal end of first metacarpal bone. a. radial deviation position. b. neutral position. c. ulnar deviation position.

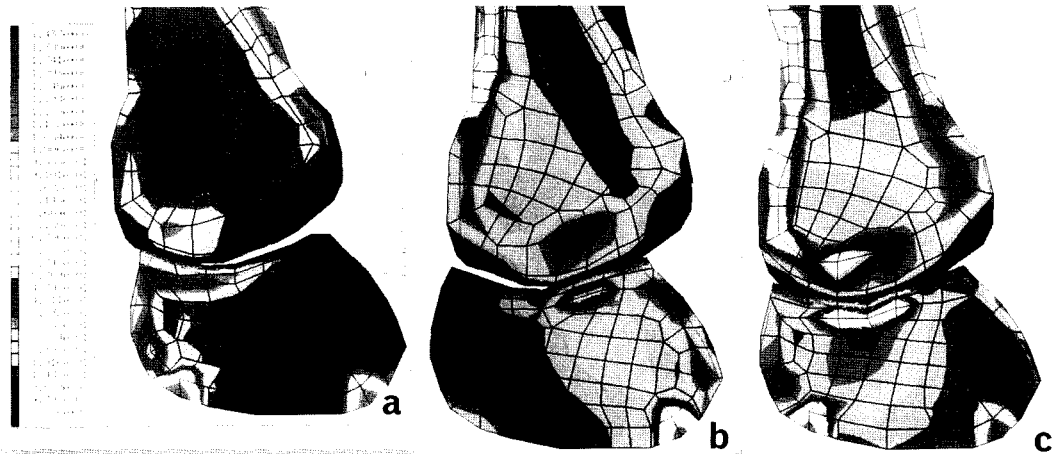
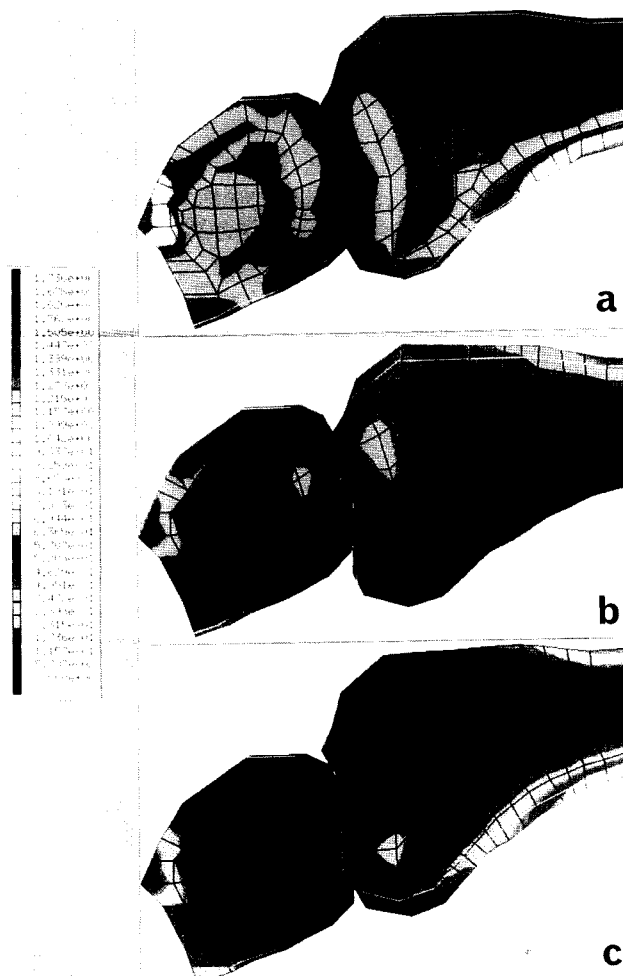


Fig. 3 Anteroposterior view of FEM image of abnormal position showing stress concentrated in the trapezium and proximal end of first metacarpal bone. a. radial shift position. b. ulnar shift position. c. shallow articular surface of trapezium.

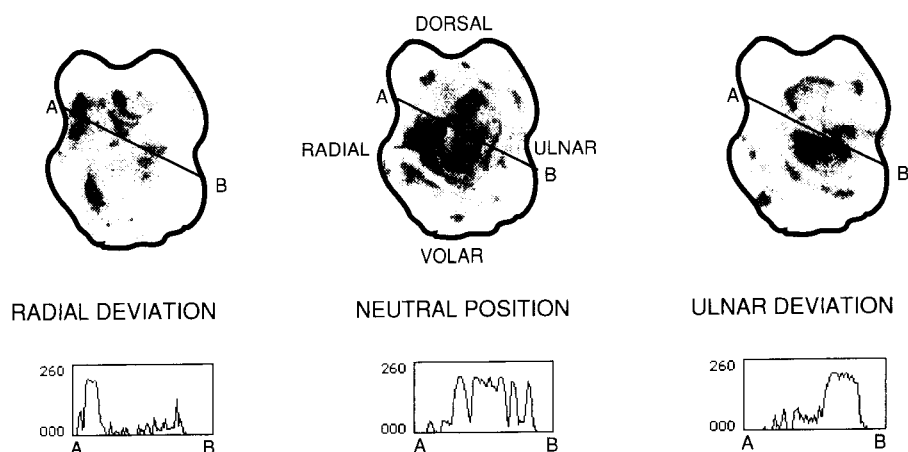


at the radial side of the trapezium (Fig. 2). Stress appeared to be evenly distributed also in the lateral view model at each angle. However, stress was slightly concentrated on the volar side of both the first metacarpal and the trapezium at all angles. Stress analysis of the anteroposterior view of FEM images in the abnormal position and abnormal configuration showed high stress concentration in each model. Stress concentrated at the radial side in the radial shift model, at the ulnar side in the ulnar shift model, and at the central part in the shallow articular model of the trapezium (Fig. 3).

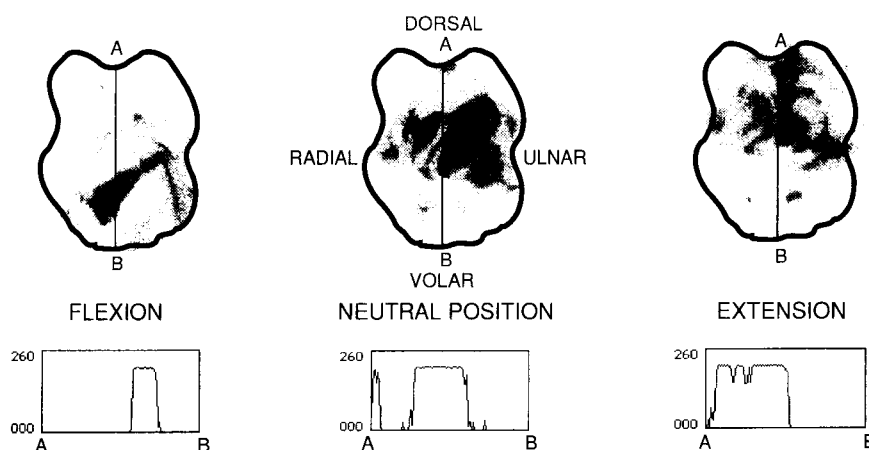
The lateral view of the FEM model of abnormal positions also showed stress concentration in the trapezium and proximal end of the first metacarpal bone. Stress was concentrated at the dorsal area in the volar shift position and occurred at the volar area in the dorsal shift position (Fig. 4). The FEM analysis depicted stress that was evenly distributed under normal pressure and position, which became concentrated locally with minimal displacement.

**Pressure-loading experiment.** The pressure-loading test showed that in the radial deviation position, the high-stress area was on the radial side of the CMJ. In

Fig. 4 Lateral view of FEM image of abnormal position showing stress concentrated areas in the trapezium and proximal end of first metacarpal bone. a. neutral position. b. volar shift position. c. dorsal shift position.



**Fig. 5** Composite plots of points of high pressure-sensitive film from radial deviation to ulnar deviation. The lower graphs show the magnification of pressure on each AB line. Vertical axis is black and white gradient.



**Fig. 6** Composite plots of points of high pressure on pressure-sensitive film from flexion to extension. Legend to the lower graphs is the same as that of Fig. 5.

the neutral position, the area of concentration increased in the central portion of the joint. In the ulnar deviation position, the stress concentration was in the rather ulnar part. A high-loading area appeared in the dorso-radial region and the concentrated area was smaller in the radial deviation position (Fig. 5). The lower graphs of Fig. 5 shows the comparative magnification of pressure on each AB line. Low pressure areas were observed on the opposite side of the high-loading area. Contact areas were small in the radial deviation position. In the ulnar devia-

tion position, the high loading area remained in the central area. The concentrated area was comparatively larger than in the ulnar deviation position. The areas of stress concentration shifted from the volar to the dorsal side during flexion-extension movement (Fig. 6). The lower graphs in Fig. 6 also show the comparative magnification of pressure on each of the AB lines. The high-loading areas were homogeneous in any position from flexion to extension. The contact areas were small in the flexion position.

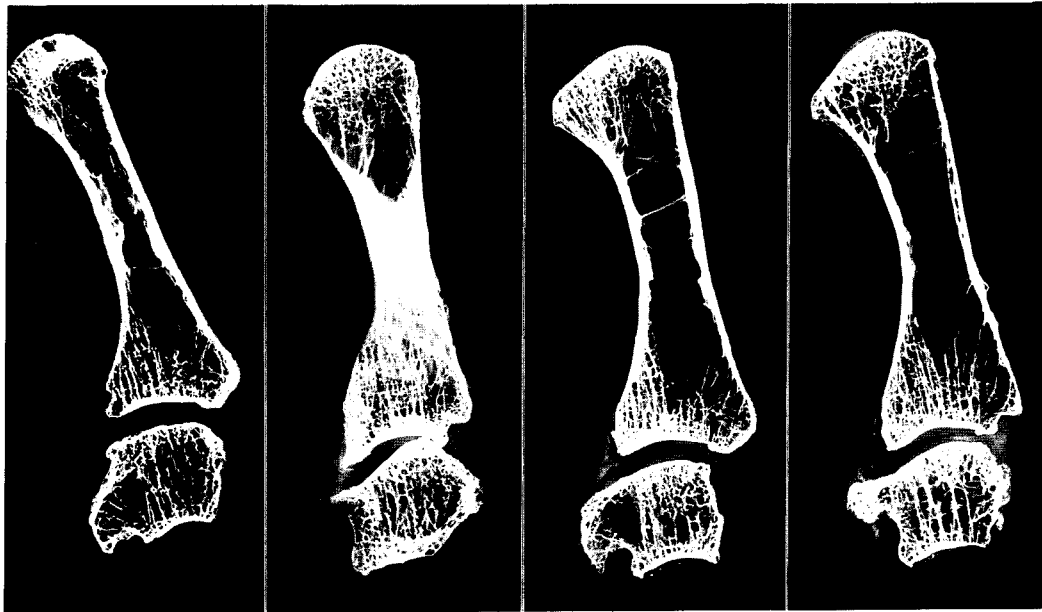


Fig. 7 Serial microradiograms of a sagittally sectioned joint. Specimens from the radial side to the ulnar side. Each section is 2-mm wide.

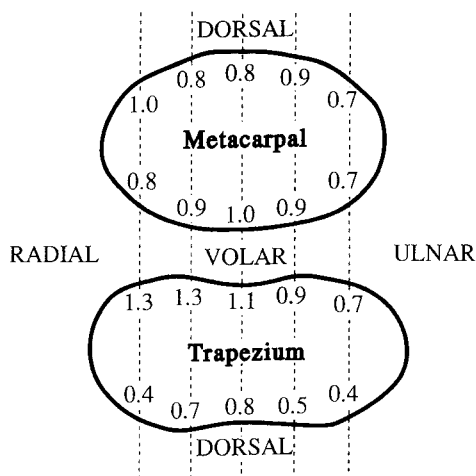


Fig. 8 The average length of the spur in each area of carpo-metacarpal joint (CMJ).

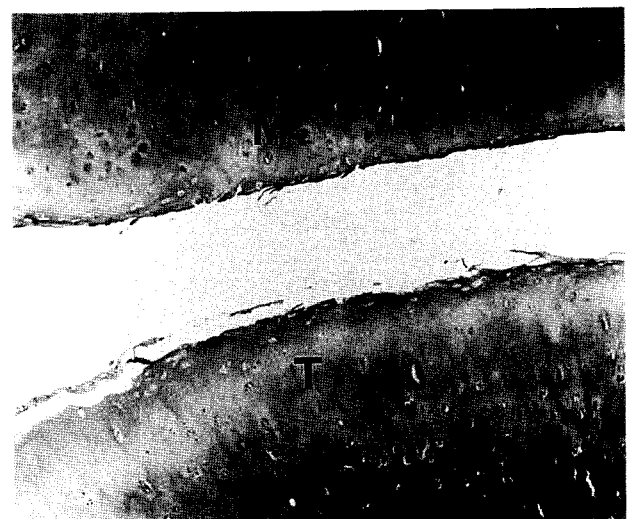


Fig. 9 Cartilage degeneration in the CMJ. (safranin-O,  $\times 66$ ) M: metacarpal bone, T: Trapezium. CMJ: See Fig. 8.

**Conventional roentgenographical, microradiographical and histological observations.** The conventional roentgenographical changes included narrowing of the CM joint space, sclerosis of the subchondral bone, osteophytes, cyst formation and joint subluxation. According to North's classification, 4 speci-

mens were stage I, 14 were stage II, 28 were stage III, and three were stage IV.

Spur formation, a buttress reaction which was visible on microradiograms, indicated that both the first metacarpal and trapezium were involved (Fig. 7). The length and area of spur formation were greater on the radial and volar



**Table 1** The grade of idiopathic osteoarthritis (OA) changes in each area of the specimens

Site of bone specimens	Grade of OA changes (%)			
	-	±	+	++
Metacarpal bone				
Volar	7	21	36	36
Central	57	14	29	0
Dorsal	14	21	51	14
Trapezium				
Volar	43	29	14	14
Central	65	7	21	7
Dorsal	43	50	0	7

(-): normal; (±): erosion; (+): fibrillation; (++) : cartilage loss

sides of both bones (Fig. 8). The spurs were larger on the trapezium in that area.

Safranin-O staining in the histological study showed the primary stage of degeneration of the joint surface of the trapezium to be on the radial side in every specimen (Fig. 9). In contrast, degeneration existed in the palmar region of the base of the first metacarpal. Bony defects were observed in some areas of the first metacarpal bones of the volar side and the radial sides of the trapezium bone. The grade of OA changes in each area of the specimens is shown in Table 1. Spurs identified in this study occurred in high-stress areas, and spur formation existed at the edge of the trapezium rather than at the surface of the first metacarpal base, according to roentgenographical and histological observations. The degenerative changes of the trapezium were observed mostly on the radial side of the joint, and on the volar side of the first metacarpal base.

## Discussion

It has been hypothesized that OA changes in the first CMJ may occur according to the characteristics of stress transmitted across the joint (2, 3), and to the special configuration of the CMJ (7) because of the prevalence of OA in this joint (9). The biomechanical relationships between the geometric forms and stress concentration on the articular surfaces of the first CMJ has received more attention recently (9, 10, 11). Other reports indicated a close relationship between the development of OA and the histomorphological appearance of the cartilage (12-14).

The shape of the joint determines its instantaneous

axis of rotation, and the moment arm is the distance from the applied load to this axis. Universal joints, including the saddle joint, allow motion about two axes of rotation that are perpendicular to each other, but not perpendicular to the anatomical planes. The CMJ was modeled in our study as a dual-axis joint with the axes perpendicular to each other, with the flexion-extension instantaneous center in the trapezium, and the radio-ulnar deviation axis in the metacarpal base (6). Stability of this important joint depends on several small ligaments that tighten during opposition and power pinch to prevent the articular surfaces from separating as they twist on themselves. In these positions, forces are unevenly distributed over the joint surfaces even under normal conditions, and wear will inevitably occur with time.

The first CMJ is a saddle joint that makes multi-directional movement possible and has a well designed configuration that disperses the stress fairly well. Unfortunately, stress concentrates mechanically on the volar side of the first metacarpal base and on the radial side of the trapezium bone in every motion. Additional simulations by FEM from studies of abnormal configuration in the joint, show that stress is quickly increased and concentrated by minimal dislocation. This supports our contention that a slight dislocation via instability due to ligamentous laxity can disrupt the organization of this joint, and this can easily lead to a degenerative cycle.

There are still many theoretical problems associated with applying FEM models to the fields of biomechanics. The theoretically applicable models now includes the two- and three-dimensional models, surface models, and volume models. The procedures for generating an accurate configuration of the model are important but the techniques are still somewhat primitive. The methods of data acquisition of the configuration from medical technology including computed tomography or magnetic resonance imaging are still being refined. Material properties of cartilage, cancellous, cortical and subchondral bones are still hypothetical. The loading direction associated with the boundary conditions that include correspondence to the bony trabeculae have to be decided theoretically.

An accurate biomechanical description of the CMJ is also important for making the CMJ model. FEM analysis can yield clinically useful and valid results with single bones and simple joints, however if the joint contact becomes more complex and there are many axes of joint movement and multiple instant centers, FEM analysis becomes further complicated. The reliability of FEM

analysis must also be verified by other methodologies. Then the results of FEM model analysis can produce a reliable biomechanical model.

Quantitative evaluations of the load transmission through the CMJ has been the subject of a few biomechanical studies, as this is a difficult field to study for technical reasons. Data have been collected on the degree and area of loading in the CMJ in normal cadavers. The saddle-shaped articular surface has been identified as the primary reason why this joint is predisposed to the development of OA (15–17). Loads applied across the CMJ during strong grasp could reach as high as 120 kgf (1180 N) (2). Certain positions, including pinch or grasp may bring the saddle articular surfaces into an incongruent contact position, resulting in a reduction in the area of contact and, thus, an increase in contact stresses even when the applied loads are unchanged (18). The decreases in contact areas resulting in increases in the stress concentration in these areas are believed to be responsible for the development of the focal degenerative lesions frequently observed in the dorso-radial and volar-ulnar regions of the CMJ (19, 20). Eaton *et al.* found that most CMJ were more congruent along the radioulnar direction than the dorso-volar direction and, globally, female joints were found to be less congruent than male joints (21).

OA of the CMJ is a condition that occurs most frequently in middle-aged women. Many different opinions supported by clinical observations have been advanced to determine the type of CMJ contour most likely to lead to the development of OA. North and Rutledge (1) found that the trapezial surface tends to be flatter in healthy women and also in joints with early OA changes. According to them, the shallow articular surface of the trapezium may predispose the CMJ to the development of OA. In our computer simulation analysis, the shallow trapezial surface is one of the most important causes of stress concentration.

The stability of the CMJ is dependent on both the unique hard tissue contour of its articular surfaces and the integrity of its ligamentous support. Ligamentous injury which causes joint hypermobility also contributes to the development of OA. Inflammatory disease can also produce ligament laxity resulting in instability and eventually OA. Inherited joint incongruency or incongruency induced by ligamentous laxity may be the major causal factors for OA of the CMJ. Rotation of the CMJ, even without ligamentous laxity, can result in joint incongruency with stress concentration on the dorso-radial and

volar-ulnar regions of the joint (19). Various histological findings and spur formation can be regarded as secondary phenomena produced by primary degeneration of the articular cartilage or stress concentration. High-contact-stress concentration may become the regions of cartilage erosion that eventually result in clinical manifestations of OA (18).

The results of the three analyses in the current study correlated closely. According to the results of our analysis of the abnormal positioning using FEM, we think that any displacement or dislocation has the potential to start a degenerative cycle, and we agree with previous reports that the abnormal positioning may result from ligamentous laxity due to aging or overstretching, especially of the ligament between the first and second metacarpal bones. The joint can become slightly dislocated radially and dorsally, which is the main type of subluxation of this joint. The form of the joint, the motion of the segments, and the moment arms for applied load are interrelated.

We have concluded that early anatomical restoration after a fracture, ligamentous injury, or the minimal stage of an idiopathic anomalous configuration like the shallow female trapezium may effectively interrupt the degenerative cycle. Osteotomy of the first metacarpal base or trapezium bone to change the direction of pressure and the stress distribution between these two bones is indicated. For example, an osteotomy to modify trapezial articular contours may be very difficult technically, however, it may be preferable to a metacarpal osteotomy because a more deeply contoured trapezium makes a better fit by increasing the total area of contact.

This is a preliminary study with small sample size testing limited ranges of motion. However, the close correspondence of the three approaches indicates that this kind of study may be fruitful when expanded to include more degrees and directions of motion. Such a study would include refinements in technique in each of the three approaches.

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